

Evaluating the use of the massive coral *Diploastrea heliopora* for paleoclimate reconstruction

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[1] To date, coral-based paleoclimate research in the Pacific has primarily utilized core samples from the genus *Porites* and has been most successful reconstructing past variability on interannual timescales, particularly the El Niño Southern Oscillation (ENSO). The Indo-Pacific coral genus *Diploastrea*, however, owing to its slower extension rate, denser structure, and longer lifespan, can potentially preserve geochemical proxy records 2–3 times longer than *Porites* cores of the same length. Before its potential can be realized, *Diploastrea* must first be calibrated and its climate signal assessed. We present oxygen isotope ($\delta^{18}\text{O}$) and Sr/Ca results from two *Diploastrea* cores collected in Fiji ($16^{\circ}49'\text{S}$, $179^{\circ}14'\text{E}$) that allow for simultaneous evaluation of this coral's paleoclimatic utility and the reproducibility of each tracer at this site. Comparison to a *Porites* record from the same location allows for further evaluation of *Diploastrea* as a paleoclimatic archive. We demonstrate that *Diploastrea*'s septal and columellar material yield similar $\delta^{18}\text{O}$ -SST relationships and that despite some sacrifice of the seasonal $\delta^{18}\text{O}$ amplitude, bulk sampling of either region is satisfactory for resolving interannual and lower frequency modes of climatic variability. Therefore paleoclimate reconstructions employing either a septal or columellar sampling regime of this genus may be useful at filling in spatial and temporal sampling gaps which currently hinder the reconstruction of long-term changes in major climate fields in the western Pacific. *INDEX*

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1. Introduction

[2] The potential utility of coral geochemical proxy records to examine changes in past Pacific Ocean conditions is enormous given the short and sparse instrumental climate record, especially in the western Pacific. The chemistry of the aragonitic skeleton of *Porites* corals has proven to be a very powerful tool in reconstructing various features of the coupled oceanic-atmospheric system including sea surface temperature (SST), sea surface salinity (SSS), and the oxygen isotopic composition of seawater [e.g., Dunbar and Wellington, 1981; Cole and Fairbanks, 1990; Cole et al., 1993; Quinn et al., 1993; Dunbar et al., 1994; Linsley et al., 1994; Wellington et al., 1996; Charles et al., 1997; Linsley et al., 2000b; LeBec et al., 2000; Hendy et al., 2002].

[3] The coral genus *Porites* has been the primary Pacific coral archive used to reconstruct past ENSO-scale climate

variability [McConnaughey, 1989; Cole and Fairbanks, 1990; Dunbar et al., 1994; Urban et al., 2000; Tudhope et al., 2001]. However, very few Pacific *Porites* records exist in ENSO-sensitive regions that span more than 100 years [Cole et al., 1993; Dunbar et al., 1994; Quinn et al., 1998; Boisseau et al., 1998; Cole et al., 2000; Linsley et al., 2000a; Urban et al., 2000], a significant limitation in addressing climate variability with decadal and multidecadal periodicity. The massive coral genus *Diploastrea*, however, has an extension rate 2–3 times slower than *Porites*, which in itself suggests that cores from comparably sized *Diploastrea* colonies should yield longer proxy records than equal length cores from *Porites* colonies. Additionally, *Diploastrea* has a dense skeletal structure that is resistant to boring organisms, grazing fish, and the destructive crown-of-thorns starfish, promoting a longer lifespan [Veron, 1986]. Last, unlike *Porites*, the genus *Diploastrea* comprises only a single species, eliminating the potential confusion of unknown proxy systematics among different individual *Porites* species.

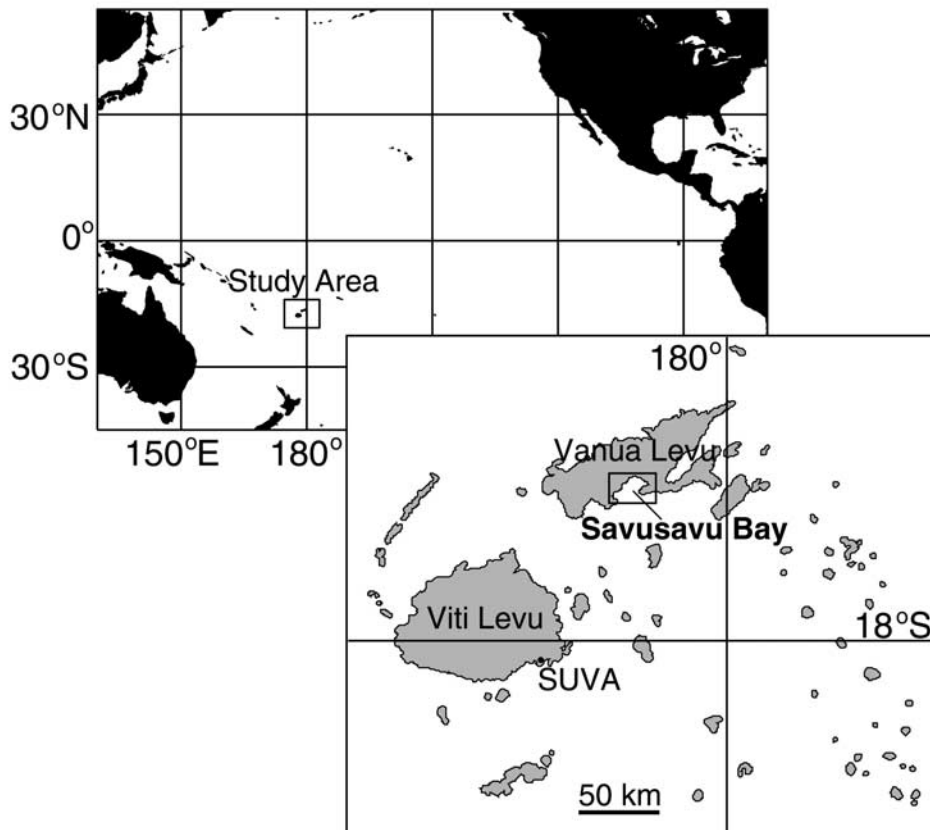


Figure 1. Location map showing Fiji's position in the western subtropical South Pacific and an enlargement of the study area, Savusavu Bay on the northern Fijian island of Vanua Levu.

[4] Here we compare the effect of sampling different skeletal elements of Fiji *Diploastrea* on the amplitude of the seasonal $\delta^{18}\text{O}$ cycle, the $\delta^{18}\text{O}$ -SST calibration, and mean annual $\delta^{18}\text{O}$. Measurements of *Diploastrea* skeletal Sr/Ca are used here mainly to aid in chronology development, but also in this case appear to provide an independent measure of SST variability that is not obscured by the evaporation-precipitation balance. Complete resolution of the entire annual cycle amplitude is not necessary to accurately determine past interannual to interdecadal climate variability [Quinn *et al.*, 1996]. We therefore test a new *Diploastrea* sampling regime that we argue will efficiently and accurately capture the long-term climate signal, while maximizing the amount of climate information retrieved from each geochemical analysis. Comparison of two *Diploastrea* time series to an adjacent *Porites* record from Fiji [Linsley *et al.*, 2004] further validates our sampling techniques, and illustrates the reproducibility of $\delta^{18}\text{O}$ and Sr/Ca in these neighboring Fiji corals. A discussion of *Diploastrea*'s ability to accurately resolve both interdecadal and trend components of climate variability at this site can be found in the work of Bagnato [2003].

2. Study Area

[5] The Fiji Islands lie in the western subtropical South Pacific and consist of approximately one hundred small

islands and two large main islands, Viti Levu and Vanua Levu. Corals were collected from Savusavu Bay, a large bay open to the Koro Sea, on the northern Fijian island of Vanua Levu ($16^{\circ}49'\text{S}$, $179^{\circ}14'\text{E}$) (Figure 1). Four rivers empty into Savusavu Bay: The Ndreke ni wai, the Lango lango, the Vianga, and the Na Tua vou. The average SST in this region is 27.3°C , with an annual range of about 4°C . Although Fiji lies significantly south of the equator and outside the heart of the western Pacific Warm Pool, this site is well positioned to record the activity of the South Pacific Convergence Zone (SPCZ), and the Southern Oscillation (SO). *Diploastrea*'s geographic range covers much of the Indo-Pacific Warm Pool, allowing the possibility for studying climatic connections between the Indian and western Pacific Oceans, including the ENSO system, and the Asian monsoon.

[6] Based on instrumental data back to 1958, the axis of SPCZ maximum rainfall extends from New Guinea toward French Polynesia, passing between Fiji and Samoa [Folland *et al.*, 2002]. The SPCZ is a dominant feature of the Southern Hemisphere subtropics, and its position and activity are modulated by the ENSO and the Interdecadal Pacific Oscillation (IPO) [Trenberth, 1976; Kiladis *et al.*, 1989; Vincent, 1994; Folland *et al.*, 2002]. When the SPCZ migrates to the northeast during El Niño events, drier than average conditions exist in Fiji; southward displacement of the SPCZ during La Niña events brings wetter than average

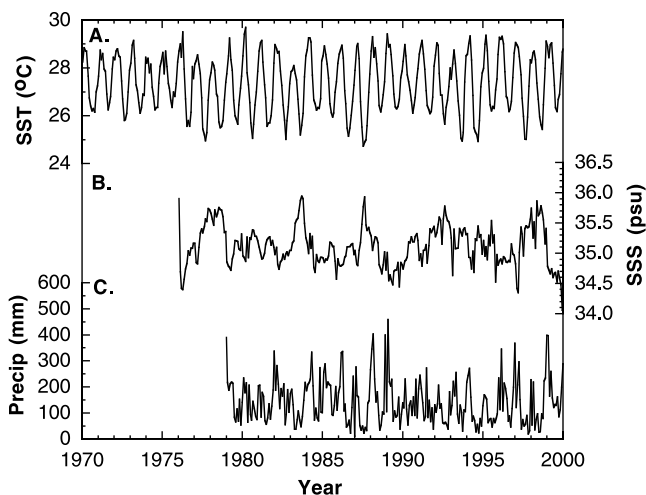


Figure 2. Regional climatic time series of (a) SST, (b) SSS, and (c) precipitation surrounding Fiji. While ENSO-related SST anomalies are not as pronounced as they are in other parts of the Pacific, seawater $\delta^{18}\text{O}$ anomalies due to SPCZ activity will drive coral $\delta^{18}\text{O}$ in the same direction as SST-induced changes, suggesting that a strong interannual signal is contained in *Diploastrea* skeletal $\delta^{18}\text{O}$ at this location.

conditions [Salinger *et al.*, 1995], decreasing surface salinity and presumably seawater $\delta^{18}\text{O}$. Fiji lies near a response hinge point for ENSO-related SST variability and near the southernmost displacement of the SPCZ, yielding precipitation anomalies that, relative to SST anomalies, are more strongly related to the SO [Salinger *et al.*, 1995]. Although seawater $\delta^{18}\text{O}$ measurements are not available at this location, the time series of local SST [Reynolds and Smith, 1994], SSS [Gouriou and Delcroix, 2002], and precipitation [Gouriou and Delcroix, 2002] illustrate these interannual signals (Figure 2). However, because the ENSO-related SST and interannual SPCZ effects on seawater $\delta^{18}\text{O}$ in this region force coral skeletal $\delta^{18}\text{O}$ in the same direction, we anticipate a robust interannual signal in coral skeletal $\delta^{18}\text{O}$ in Fiji.

3. Methods

3.1. Coral Collection and Sampling Considerations

[7] In April 1997, a 30-cm-long coral core (4F1) from a colony of *Diploastrea heliopora* was collected by hydraulic drill from ~ 10 m water depth from the outer edge of Savusavu Bay in Fiji, and in December 2001, a 1.3-m-long coral core (LH) was collected from a second colony in 2 m of water 0.5 km from the first core. A 2.3-m-long *Porites lutea* core (1F) [Linsley *et al.*, 2004] was also collected from the middle of Savusavu Bay in 10 m of water in April 1997. Core preparation and isotope analyses follow the procedures of Linsley *et al.* [2000a]. The cores were washed with fresh water, dried and sectioned into 7-mm-thick slabs along the major growth axes using a band saw. The slabs were then X-rayed to reveal the annual density bands. The slabs were cleaned with deionized water in an ultrasonic bath for approximately 15 min to dislodge saw cuttings, then placed

in a drying oven at 40°C overnight. All subannual samples were collected using a Dremel[®] Tool with a diamond micro drill bit under a binocular microscope along corallite traces identified both by eye and on the X-radiograph positives. Each core was continuously sampled every 0.5 mm along the axis of maximum growth, excavating an ~ 2 mm square groove in the coral slab throughout the upper 50 mm for calibration purposes, with a coarser 1 mm sample resolution below 50 mm depth.

[8] The width of a sampling transect in *Porites* cores usually incorporates 3–4 corallites because the individual corallite diameters are small. This averaging of material from 3–4 individual corallites of the colony is unavoidable with bulk sampling methods but is, however, thought to minimize the effects of any spatial geochemical variations in the skeleton [Gagan *et al.*, 1994]. While growing at a rate 2–3 times slower than *Porites*, *Diploastrea* corallites are also 4–5 times larger than *Porites*, and clearly visible on X-radiographs (Figure 3). An individual corallite is composed of an elaborate inner portion called the columella that is surrounded by radiating septal plates that thicken toward the corallite wall (Figure 3). For corals with larger corallites, like *Diploastrea*, there is concern that the growth surfaces of these different skeletal elements may not be parallel and therefore may show isotopic heterogeneity along sampling horizons [Land *et al.*, 1975; Dodge *et al.*, 1992; Leder *et al.*, 1996; Watanabe *et al.*, 2003]. This problem is complicated by the possible complex saw tooth-like pattern of synchronous time horizons [Leder *et al.*, 1996], suggesting that wide sampling tracks with a mixture of skeletal elements may result in reduced sensitivity due to time averaging. The recent study by Watanabe *et al.* [2003] was the first to evaluate the spatial heterogeneity of $\delta^{18}\text{O}$ in different skeletal elements of *Diploastrea* using two corals from the western Pacific. The authors found that high-resolution (100 μm interval) sampling of columellar material, using the method of Gagan *et al.* [1994], yields the highest seasonal amplitude and recommended preferential sampling of this inner skeletal material to best capture the full annual cycle. The muted septal signal was attributed to the potentially angled growth surface of septal elements, while columellar material may form more perpendicular to the major growth axis.

[9] To address this significant sampling concern for *Diploastrea* and to establish an efficient sampling regime for extracting the interannual and interdecadal climate signal from the Fiji *Diploastrea* cores, time-synchronous sample transects were made in the upper 50 mm of core 4F1. One transect incorporated only septal material, while a second, parallel transect incorporated the columellar material of the same corallite (Figure 4). Both paths were sampled continuously at 0.5 mm increments.

3.2. Stable Isotope Mass Spectrometric Analysis

[10] For each sample, approximately 200 μg of coral powder was dissolved in 100% H_3PO_4 at 90°C in a Multi-Prep sample preparation device, and the resulting CO_2 gas was analyzed using a Micromass Optima gas-source triple-collector mass spectrometer at the University at Albany, State University of New York stable isotope laboratory. The total number of subannual samples analyzed from core 4F1

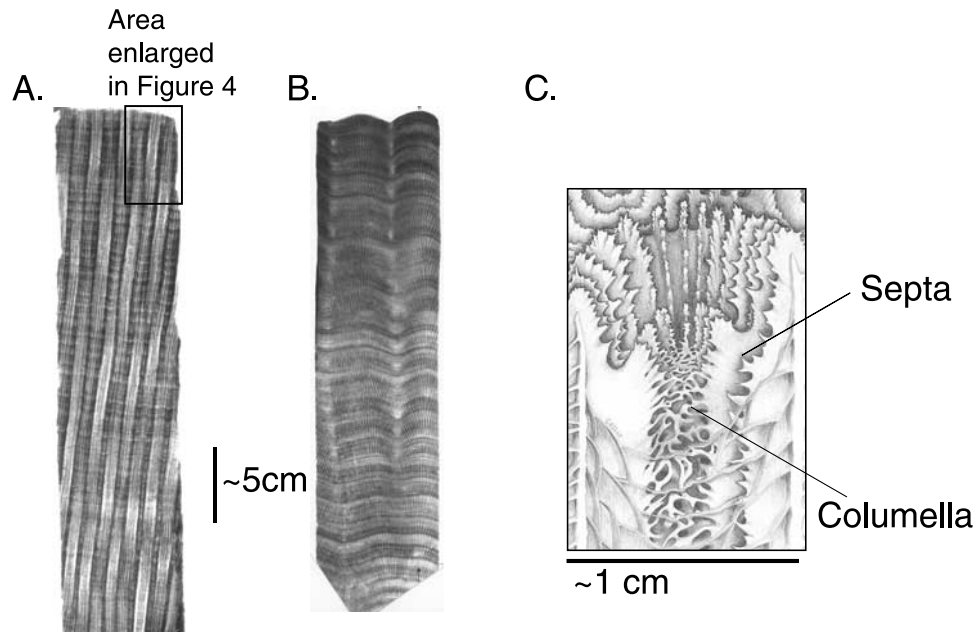


Figure 3. X-radiograph positives of the upper ~ 30 cm of (a) Fiji *Diploastrea* core 4F1 and (b) Fiji *Porites* core 1F, both collected in April 1997. The two genera are physically quite different, with *Diploastrea* having much larger corallites and 2–3 times as many annual density bands than *Porites*, the latter resulting in a longer paleoclimatic record for the same length of core. (c) Corallite architecture sketch, modified from *Veron* [1986]. While this illustration is not of a *Diploastrea* corallite, it adequately shows the septal and columellar regions, which can have different isotopic values along sample horizons perpendicular to the major growth axis.

was 554, with approximately 10% of these being analyzed in duplicate. During the course of analyzing core 4F1, the standard deviation of the isotopic compositions of international standard NBS-19 was 0.035‰ for $\delta^{18}\text{O}$ ($n = 100$). The average difference between the replicate coral samples analyzed was 0.06‰ for $\delta^{18}\text{O}$ ($n = 70$). The total number of subannual samples analyzed from core LH was 1343, with approximately 10% of these being analyzed in duplicate. During the course of analyzing core LH, the standard deviation of NBS-19 was 0.034‰ for $\delta^{18}\text{O}$ ($n = 258$). The average difference between replicate samples analyzed was 0.07‰ for $\delta^{18}\text{O}$ ($n = 174$). We present here only data from the last 60 years, all reported as per mil deviations relative to Vienna Pee Dee belemnite (VPDB).

3.3. ICP-AES Analysis

[11] For each septal sample, approximately $100\ \mu\text{g}$ of coral powder was dissolved in ~ 2 mL of 2% HNO_3 and introduced as an aerosol to a Jobin-Yvon Panorama inductively coupled plasma atomic emission spectrophotometer at the Lamont-Doherty Earth Observatory (LDEO) of Columbia University, using procedures similar to those described by *Schrag* [1999]. Measurement of the Sr/Ca ratio was made on splits of the same sample powders analyzed for $\delta^{18}\text{O}$. A total of 235 subannual samples were analyzed from core 4F1, with approximately 10% being analyzed in duplicate. During the course of the analyses, the average relative standard deviation of the replicate samples analyzed was 0.22% ($n = 18$). A total of 245 subannual samples were analyzed from core LH, with approximately 10% being

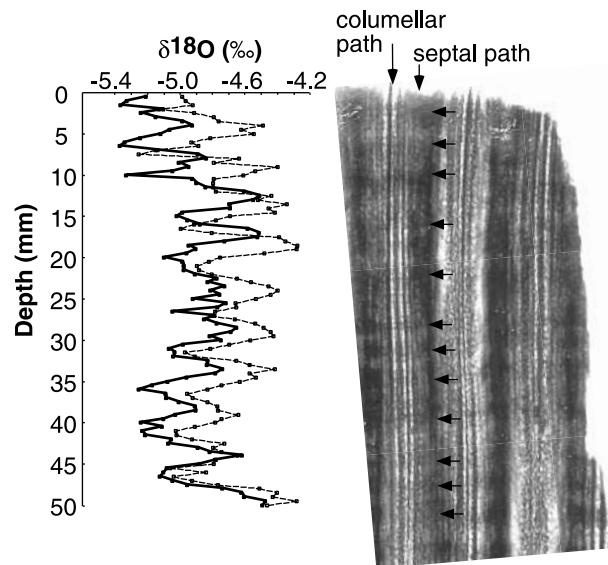


Figure 4. Oxygen isotope time series from the experimental sample transects in the upper 50 mm of *Diploastrea* core 4F1 utilizing septal material (solid line), and columellar material (dashed line), plotted to scale with the X-radiograph of the corallite from which they were sampled. Arrows show the location of high-density bands. There is a 0.2 to 0.4‰ offset between the two transects in the upper 20 mm, which is reduced below 20 mm depth.

analyzed in duplicate. During the course of the analyses, the average relative standard deviation of the replicate samples analyzed was 0.18% ($n = 24$).

3.4. Chronology

[12] Although density banding in *Diploastrea* is not distinct over the entire length of the cores, distinct sections appear annual. Oxygen isotopic and Sr/Ca analyses, on the other hand, show a strong and obvious annual cycle. Therefore the annual periodicity of skeletal $\delta^{18}\text{O}$ and Sr/Ca was used to develop the chronology for the cores. Using satellite-derived monthly SST data from the $2^\circ \times 2^\circ$ grid encompassing Savusavu Bay [Reynolds and Smith, 1994], the $\delta^{18}\text{O}$ and Sr/Ca data (from the same samples) were tuned to the SST record by assigning the lowest (highest) $\delta^{18}\text{O}$ and Sr/Ca values of each year to the highest (lowest) SST [Bagnato, 2003]. Age assignments were then linearly interpolated between these two annual anchor points using the Arand software package (P. Howell, personal communication, 2002), which unavoidably introduces a couple of months of error because corals do not grow uniformly throughout the year. A continuous monthly SST data set is available only as far back as 1970, so for age assignments before 1970 the lowest (highest) $\delta^{18}\text{O}$ and Sr/Ca values were assigned to March (August), March and August being the average times of highest and lowest SST, respectively, between 1970 and 1997. It should be noted that these temperature extremes do vary from year to year, introducing the potential for additional temporal error on the order of 1 to 2 months in years prior to 1970. Within the calibration interval (upper 50 mm), our sampling regime returns 10 ± 1 samples per year, while lower resolution sampling below 50 mm in each core yields 5 ± 1 samples per year. Because the gridded SST data used for calibration are monthly while the coral isotope data have unequal time steps, all data were linearly interpolated to 6 points per year using the Arand software package (P. Howell, personal communication, 2002) to facilitate comparison of the records, with subsequent annual averages calculated from these roughly bimonthly time series. *Diploastrea* $\delta^{18}\text{O}$ and Sr/Ca data are available from the World Data Center for Paleoclimatology, 325 Broadway, Boulder, Colorado (<http://www.ngdc.noaa.gov/paleo/paleo.html>).

4. Results

4.1. Columellar Versus Septal $\delta^{18}\text{O}$

[13] Figure 4 shows the experimental sampling transects made in *Diploastrea* core 4F1 from Fiji plotted to scale with the X-radiograph of the corallite from which they were sampled. Low-density bands are generally thicker than the high-density bands, and $\delta^{18}\text{O}$ maxima and minima generally correspond to the low- and high-density bands, respectively, although, as mentioned above, the density banding is not distinct over the entire length of the core. Columellar $\delta^{18}\text{O}$ on average has a greater seasonal amplitude than septal $\delta^{18}\text{O}$ for the ten-year calibration interval. Of additional importance is the timing of the seasonal cycles in each transect. Within the upper ~ 20 mm of core 4F1 the columellar $\delta^{18}\text{O}$ signal is offset 1–1.5 mm deeper from the corallite growth surface than septal $\delta^{18}\text{O}$. Below ~ 20 mm, both $\delta^{18}\text{O}$ signals

are in phase with little to no lag. Both transects, however, show similar year-to-year variability over this ten-year period.

[14] After temporal conversion of the two $\delta^{18}\text{O}$ transects, we compared annual minima and maxima in regional SST [Reynolds and Smith, 1994] and coral $\delta^{18}\text{O}$ over the time period 1987–1997 (Figure 5a) to Fiji *Porites*. Restricting this regression analysis to the tie points used in the age model excludes the coral data that have the greatest chronological uncertainty due to linear interpolation between the tie points [Watanabe et al., 2003]. The least squares regression equations for the experimental transects are shown in Table 1. Although the septal and columellar $\delta^{18}\text{O}$ -SST calibrations have similar slopes ($-0.15\text{‰}/^\circ\text{C}$ and $-0.16\text{‰}/^\circ\text{C}$, respectively), the slopes of both calibrations are more shallow than that of Fiji *Porites* ($-0.18\text{‰}/^\circ\text{C}$) from this location (Figure 5a), and the New Caledonia *Diploastrea* record ($-0.18\text{‰}/^\circ\text{C}$) [Watanabe et al., 2003]. Because in Fiji SST and SSS should affect coral $\delta^{18}\text{O}$ nearly equally, the $\delta^{18}\text{O}$ -SST relationship could be biased to some degree by SSS variability. Therefore the above regression technique was repeated for septal Sr/Ca over the same time period (Figure 5b). The derived Sr/Ca-SST relationship for *Diploastrea* is -0.034 mmol/mol/ $^\circ\text{C}$ (Table 1), which is less than the slope found for Fiji *Porites* (-0.054 mmol/mol/ $^\circ\text{C}$).

[15] To evaluate the potential of using *Diploastrea* to reconstruct long-term local and regional conditions and variability, annual average septal and columellar $\delta^{18}\text{O}$ are compared to annual average SST for this region in Figure 6. Annual average $\delta^{18}\text{O}$ data for the calibration interval (1987–1996) should be a good measure of the ability of each part of the skeleton to record average conditions in a given year. Figure 6 shows that both parts of the *Diploastrea* skeleton yield comparable relative interannual $\delta^{18}\text{O}$ signals that track the observed SST variations, despite their offset in absolute $\delta^{18}\text{O}$ values.

4.2. Comparison of Fiji Corals and Regional Differences in Mean Climate

[16] Figure 7 shows the $\delta^{18}\text{O}$ and Sr/Ca values measured on septal skeleton for both Fiji *Diploastrea* cores. The annual cycles for $\delta^{18}\text{O}$ and Sr/Ca (from same samples) are phase-locked at zero lag, making the timing of either tracer a valid chronology tool. After temporal conversion, annual average $\delta^{18}\text{O}$ and Sr/Ca values were calculated and the resulting time series since 1940 are presented in Figure 8, plotted as anomalies relative to the 1970–1996 average for each core. The relative changes in $\delta^{18}\text{O}$ and Sr/Ca from the two *Diploastrea* cores are in general agreement. In addition, despite the likelihood of losing part of the seasonal cycle by sampling septal material, interannual variations in annual average *Diploastrea* $\delta^{18}\text{O}$ and Sr/Ca are comparable to that of *Porites* in terms of both timing and amplitude. For comparison to the only published *Diploastrea* records [Watanabe et al., 2003], we calculated mean conditions in all measured parameters for the period 1980–1996. The average annual extension rate of *Diploastrea* from Fiji, based on the distance between consecutive $\delta^{18}\text{O}$ maxima, was 5.5 ± 1.0 mm/yr, and 5.6 ± 0.9 mm/yr for cores 4F1 and LH, respectively. Fiji *Porites* during the same time period grew at an average rate of 11 ± 1.8 mm/yr. The average $\delta^{18}\text{O}$

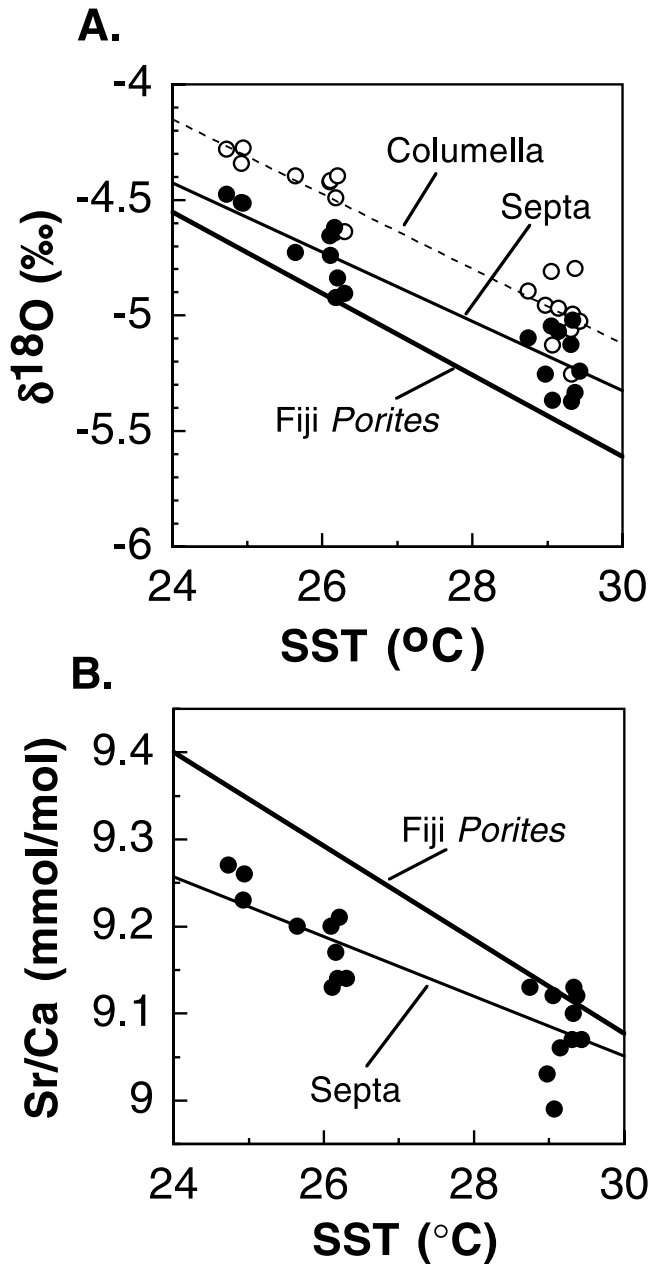


Figure 5. (a) Least squares regression of septal (solid circles and line) and columellar (open circles, dashed line) $\delta^{18}\text{O}$ and regional SST for *Diploastrea* core 4F1 from Fiji over the period 1987–1997. The Fiji *Porites* $\delta^{18}\text{O}$ -SST relationship is shown in bold for comparison. (b) Least squares regression of septal Sr/Ca (solid circles and line) and SST as in Figure 5a, with Fiji *Porites* Sr/Ca-SST relationship (bold line) for comparison.

values for the period 1980–1996 are $-4.93 \pm 0.16\text{‰}$ and $-4.80 \pm 0.23\text{‰}$ for *Diploastrea* cores 4F1 and LH, respectively, and $-5.17 \pm 0.25\text{‰}$ for *Porites* core 1F. Average Sr/Ca values for this same interval are 9.15 ± 0.04 mmol/mol and 9.16 ± 0.06 mmol/mol for *Diploastrea* cores 4F1 and LH, respectively, and 9.22 ± 0.08 mmol/mol for *Porites* core 1F. The two Fiji *Diploastrea*-*Porites* pairs

Table 1. Least Squares Regression Equations for the Temperature Dependence of $\delta^{18}\text{O}$ and Sr/Ca in *Diploastrea* Core 4F1

Skeletal Region	Equation	r Value
Septal $\delta^{18}\text{O}$	$\delta^{18}\text{O} = -0.15 * T (\text{°C}) - 0.84$	0.92
Columellar $\delta^{18}\text{O}$	$\delta^{18}\text{O} = -0.16 * T (\text{°C}) - 0.26$	0.94
Septal Sr/Ca	$\text{Sr/Ca} = -0.034 * T (\text{°C}) + 10.08$	0.84

yield an average difference in disequilibrium offset in $\delta^{18}\text{O}$ of $0.31 \pm 0.09\text{‰}$ (Table 2), which is consistent with the only other coupled $\delta^{18}\text{O}$ measurements from New Caledonia and Alor, Indonesia of $0.3 \pm 0.1\text{‰}$ [Watanabe *et al.*, 2003]. Further, if the Fiji *Diploastrea*-*Porites* offsets are converted to SST using the Fiji *Porites* calibration values (-0.053 mmol/mol/ $^{\circ}\text{C}$, and $-0.18\text{‰}/^{\circ}\text{C}$), assuming for discussion that each tracer is controlled solely by SST, the average SST offset between Fiji *Diploastrea* and *Porites* is $1.23 \pm 0.1^{\circ}\text{C}$ based on Sr/Ca, and $1.69 \pm 0.5^{\circ}\text{C}$ based on $\delta^{18}\text{O}$ (Table 2). These intergenus SST offsets in Fiji are equivalent, within one standard deviation, to the New Caledonia and Alor, Indonesia intergenus $\delta^{18}\text{O}$ offsets converted to SST ($1.78 \pm 0.6^{\circ}\text{C}$) (Table 2).

[17] To establish whether sampling regime or sampling density affect the ability of *Diploastrea* to record regional differences in mean climate conditions, we follow the comparison made by Watanabe *et al.* [2003] of the combined effect of SST and SSS differences between New Caledonia, Indonesia, and Fiji on coral $\delta^{18}\text{O}$. We add the mean Fiji coral data for 1980–1996 to the analysis of Watanabe *et al.* [2003] in Table 3. Fiji is warmer and less saline than New Caledonia (Table 3). According to the $\delta^{18}\text{O}$ -SST relationship of $-0.18\text{‰}/^{\circ}\text{C}$, the difference in mean SST between Fiji and New Caledonia should produce a change in coral $\delta^{18}\text{O}$ of 0.71‰ (Table 3). According to the $\delta^{18}\text{O}$ -SSS relationship of $0.27\text{‰}/\text{psu}$ [Fairbanks *et al.*, 1997] used in Watanabe *et al.* [2003], the difference in mean SSS between Fiji and New Caledonia should shift coral $\delta^{18}\text{O}$ by an additional 0.16‰ (Table 3). The combined

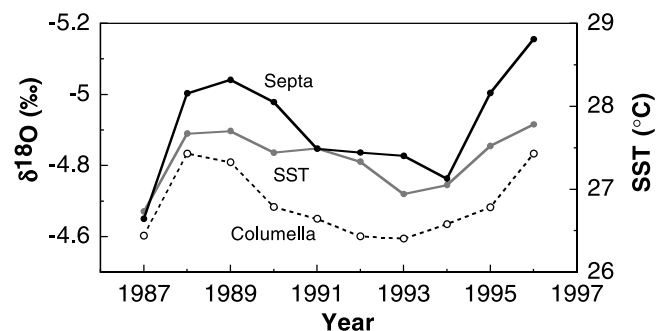


Figure 6. Annual average SST (shaded line) and $\delta^{18}\text{O}$ for septal (solid black line) and columellar (dashed line) transects from Fiji *Diploastrea* core 4F1 for the period 1987–1996. Both parts of the skeleton yield annually averaged climate signals over this ~ 10 year period that are comparable in amplitude and accurately track the observed SST changes, suggesting that for long-term climatic reconstructions either part will provide a satisfactory estimate.

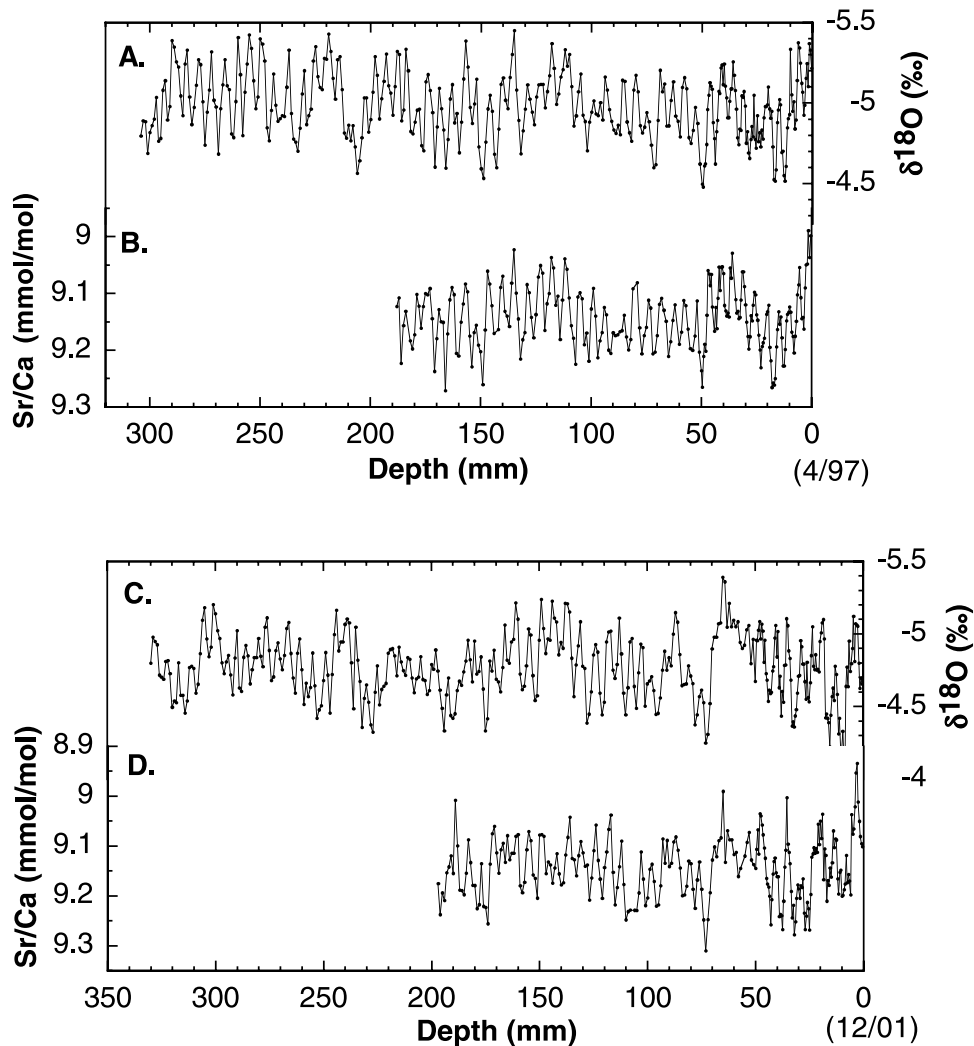


Figure 7. $\delta^{18}\text{O}$ and Sr/Ca measured on septal material of *Diploastrea* (a and b) core 4F1 and core (c and d) LH from Fiji, at ~ 10 samples per year above 50 mm depth and ~ 5 samples per year below 50 mm depth.

influence of the differences in mean SST and SSS should therefore lower Fiji coral $\delta^{18}\text{O}$ by 0.87‰ relative to New Caledonia coral $\delta^{18}\text{O}$. The regional differences in mean coral $\delta^{18}\text{O}$ between Fiji and New Caledonia indicated by *Porites* and *Diploastrea* are 0.75‰ and 0.83‰, respectively, which are very close to the expected value (Table 3). Fiji is cooler and more saline than Alor, Indonesia, and using the same $\delta^{18}\text{O}$ -SST and $\delta^{18}\text{O}$ -SSS relationships as above, the difference in mean SST between Fiji and Indonesia should shift coral $\delta^{18}\text{O}$ by 0.18‰ (Table 3), while the difference in mean SSS should shift coral $\delta^{18}\text{O}$ an additional 0.22‰ (Table 3). The combined influence of the differences in mean SST and SSS should therefore raise Fiji coral $\delta^{18}\text{O}$ by 0.40‰ relative to Alor, Indonesia coral $\delta^{18}\text{O}$ (Table 3). The regional differences in mean coral $\delta^{18}\text{O}$ between Fiji and Indonesia indicated by *Porites* and *Diploastrea* are 0.35‰ and 0.41‰, respectively, which are also very close to the expected value (Table 3). The regional differences between measured and calculated $\delta^{18}\text{O}$ are all below 0.12‰, with *Diploastrea* showing even better

agreement (below 0.04‰) than *Porites* for both comparisons (Table 3), as found by *Watanabe et al.* [2003].

4.3. Interpretation of the Fiji Coral $\delta^{18}\text{O}$ Signal

[18] Because the SPCZ is modulated in part by the ENSO [Folland *et al.*, 2002], an index of SPCZ activity is useful in establishing the target SST and seawater $\delta^{18}\text{O}$ variations in the region that we hope to reconstruct with coral $\delta^{18}\text{O}$. The SPCZ Position Index (SPI) is a station sea level pressure-based index which defines the position of the SPCZ, calculated as the normalized seasonal difference in msl pressure between Suva (Fiji) and Apia (Samoa) [Folland *et al.*, 2002]. Positive values of the SPI represent displacement of the SPCZ northeast toward Apia, while negative values represent displacement southwest toward Suva, generally creating drier and wetter than average conditions in Fiji, respectively. The NINO 4 SST anomaly index [Kaplan *et al.*, 1998] is equatorial in its coverage (5°N – 5°S , 160°E – 150°W), but also straddles the dateline and is therefore useful in documenting the effect of ENSO activity on SST

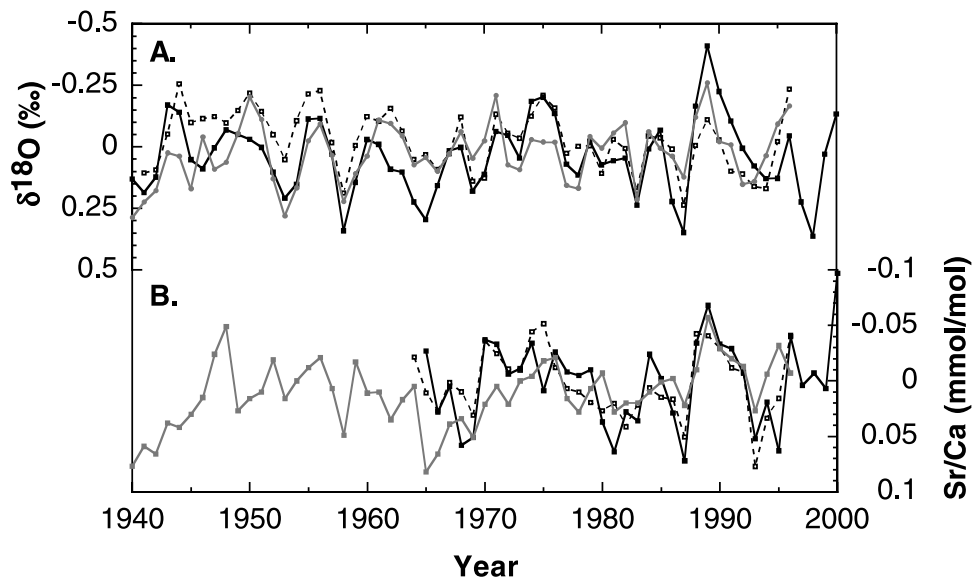


Figure 8. Annual average (a) $\delta^{18}\text{O}$ and (b) Sr/Ca for Fiji *Diploastrea* cores 4F1 (dashed line) and LH (black line), and Fiji *Porites* core 1F (shaded line) for the period 1940–2000, plotted as anomalies relative to the 1970–1996 mean for each core.

in the equatorial western Pacific. Positive values of the NINO 4 index represent El Niño conditions while negative values represent La Niña conditions, creating negative and positive SST anomalies in Fiji, respectively. Given the good agreement between Fiji coral records (Figure 8), and the roughly equal influences of SST and seawater $\delta^{18}\text{O}$ on *Diploastrea* $\delta^{18}\text{O}$ [Bagnato, 2003], the two *Diploastrea* time series have been averaged to create composite *Diploastrea* $\delta^{18}\text{O}$ and Sr/Ca records (period of overlap 1942–1997) (Figure 9), for comparison to the SPI and the NINO 4 Index. The composite *Diploastrea* record captures most transitions of the SPI and NINO 4 Index as effectively as *Porites* in terms of both timing and amplitude for this ~60 year period, with only minor differences in coral $\delta^{18}\text{O}$ and Sr/Ca near the beginning of each record.

5. Discussion

[19] We see no evidence in Fiji *Diploastrea* for the one-half- to full seasonal cycle offset between time-synchronous

septal and columellar $\delta^{18}\text{O}$ signals reported in *Diploastrea* from New Caledonia [Watanabe *et al.*, 2003]. We observe a maximum offset of 1.5 mm (~3 months) which is opposite of that observed in New Caledonia, with columellar $\delta^{18}\text{O}$ shifted down-core relative to septal $\delta^{18}\text{O}$ (Figure 4). The offset of seasonal $\delta^{18}\text{O}$ cycles in New Caledonia *Diploastrea* was attributed to skeletal thickening [Watanabe *et al.*, 2003]. However, given the opposite offset relationship seen in Fiji *Diploastrea*, a tissue layer thickness of only 5 mm, and that each transect contains the same number of seasonal cycles, the cause in Fiji is not likely due to subtle growth-related differences or tissue layer thickening and remains unclear. It should be noted, however, that Fiji *Diploastrea* corals have an average skeletal extension rate which is nearly twice that of New Caledonia *Diploastrea*. The slopes of Fiji septal and columellar $\delta^{18}\text{O}$ -SST calibrations are very similar, suggesting that different skeletal elements in Fiji *Diploastrea* likely do not calcify at significantly different times. Still, it is recommended that a single skeletal element in these large-polyped corals be sampled using as narrow a

Table 2. *Diploastrea*-*Porites* Offsets in $\delta^{18}\text{O}$ and Sr/Ca for This Study and That of Watanabe *et al.* [2003] Over the Common Period 1980–1996

<i>Diploastrea</i> - <i>Porites</i> Pair	Average $\delta^{18}\text{O}$ Offset, ‰	Average Sr/Ca Offset, mmol/mol	Average $\delta^{18}\text{O}$ Offset, °C ^a	Average Sr/Ca Offset, °C ^b
<i>This Study</i>				
Fiji 4F1-1F	0.24	0.07	1.3	1.3
Fiji LH-1F	0.37	0.06	2.1	1.1
Average	0.31	0.07	1.7	1.2
Standard deviation	0.09	0.01	0.5	0.1
<i>Watanabe et al.</i> [2003]				
New Caledonia	0.39	–	2.2	–
Alor, Indonesia	0.25	–	1.4	–
Average	0.32	–	1.8	–
Standard deviation	0.10	–	0.6	–

^aSST offset calculated using Fiji *Porites* and New Caledonia *Diploastrea* calibration ($-0.18\text{‰}/\text{°C}$).

^bSST offset calculated using Fiji *Porites* calibration ($-0.053\text{ mmol/mol}/\text{°C}$).

Table 3. Differences in Mean SST, SSS, and Coral $\delta^{18}\text{O}$ Between Published *Diploastrea* Sampling Sites for the Period 1980–1996, Following *Watanabe et al.* [2003]^a

Location/Calculation	SST	SSS	$\delta^{18}\text{O}$ <i>Porites</i> , ‰	$\delta^{18}\text{O}$ <i>Diploastrea</i> , ‰
New Caledonia	23.4°C	35.7 psu	-4.42	-4.03
Fiji	27.3°C	35.1 psu	-5.17	-4.86 ^b
Measured Δ New Caledonia-Fiji	3.9°C	0.6 psu	0.75	0.83
New Caledonia-Fiji calculated $\Delta\delta^{18}\text{O}$	0.71‰	0.16‰	0.87	0.87
Measured-calculated New Caledonia-Fiji difference	–	–	0.12	0.04
Alor, Indonesia	28.3°C	34.3 psu	-5.52	-5.27
Fiji	27.3°C	35.1 psu	-5.17	-4.86 ^b
Measured Δ Fiji-Alor	1.0°C	0.8 psu	0.35	0.41
Fiji-Alor calculated $\Delta\delta^{18}\text{O}$	0.18‰	0.22‰	0.40	0.40
Measured-calculated Fiji-Alor difference	–	–	0.05	0.01

^aRegional $\Delta\delta^{18}\text{O}$ due to SST calculated using 0.18‰/°C. Regional $\Delta\delta^{18}\text{O}$ due to SSS calculated using 0.27‰/psu.

^bFiji *Diploastrea* $\delta^{18}\text{O}$ value is average of cores 4F1 and LH.

path as possible to avoid time averaging inherent from wide sampling tracks that cross locally jagged growth surfaces. The data presented here, however, are consistent with those of *Watanabe et al.* [2003] in terms of the relative amplitudes of the seasonal $\delta^{18}\text{O}$ signals in *Diploastrea* skeletons.

[20] The slopes of the Fiji *Diploastrea* septal and columellar $\delta^{18}\text{O}$ -SST relationships are both more shallow than those observed for Fiji *Porites* and New Caledonia *Diploastrea*. The use of a regional gridded SST data set could be considered a hindrance for calibration purposes,

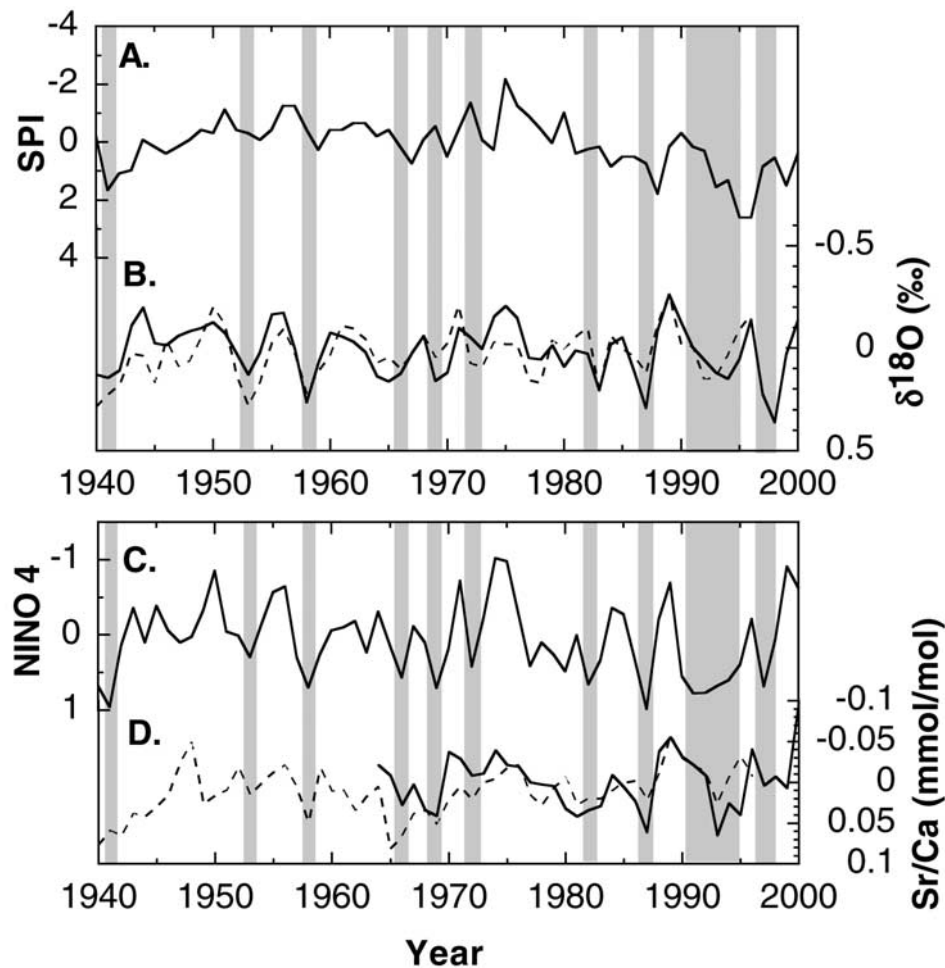


Figure 9. Annual average values of (a) the SPCZ Position Index (SPI), (b) the Fiji *Diploastrea* composite $\delta^{18}\text{O}$ (solid) and *Porites* $\delta^{18}\text{O}$ (dashed), (c) the NINO 4 SST anomaly index, and (d) the Fiji *Diploastrea* composite Sr/Ca (solid) and *Porites* Sr/Ca (dashed) time series for the period 1940–2000. All coral data are annual average anomalies relative to the 1970–1996 mean. Shading indicates timing of major El Niño events of the past ~60 years.

however, we are most interested in reconstructing long-term regional climate conditions, for which a gridded SST data set is applicable. *Watanabe et al.* [2003] have shown that in New Caledonia *Diploastrea* $\delta^{18}\text{O}$ is in good agreement with local *Porites*, with slope values of $-0.18\text{‰}/^\circ\text{C}$ and $-0.19\text{‰}/^\circ\text{C}$, respectively, using in situ SST data. Our shallow $\delta^{18}\text{O}$ -SST slopes of $-0.15\text{‰}/^\circ\text{C}$ and $-0.16\text{‰}/^\circ\text{C}$ are undoubtedly due to reduced $\delta^{18}\text{O}$ seasonal amplitude, possibly from SSS variability (i.e., enhanced evaporation in summer), or sampling bias. We favor the latter explanation, given that our sample recovery per unit time is ~ 2.5 times less than that of *Watanabe et al.* [2003] and ~ 2 times less than the Fiji *Porites* core. Indeed, low sample recovery per unit time will cause some degree of smoothing of the annual cycle, particularly during slower-growing periods. The similarity of the septal and columellar $\delta^{18}\text{O}$ -SST relationships supports this idea, indicating that there are not significant differences in disequilibrium isotope fractionation between different skeletal regions. Further, if enhanced summer evaporation, or other changes in the evaporation-precipitation balance were the cause of the reduced seasonal amplitude, we would expect the Sr/Ca-SST relationship to be unaffected, given the general consensus that coral Sr/Ca is a better SST proxy than coral $\delta^{18}\text{O}$. However, we derive a *Diploastrea* Sr/Ca-SST slope that is likewise less than that observed in Fiji *Porites*, which experienced the same environmental history.

[21] Because of our biased $\delta^{18}\text{O}$ -SST calibration, the *Diploastrea* $\delta^{18}\text{O}$ -SST calibration of *Watanabe et al.* [2003] of $-0.18\text{‰}/^\circ\text{C}$, is useful in establishing the expected annual amplitude if SST was the only influence on coral $\delta^{18}\text{O}$. The roughly 4°C annual temperature range in Fiji, would be expected to produce a coral $\delta^{18}\text{O}$ range of $\sim 0.7\text{‰}$ each year. While columellar $\delta^{18}\text{O}$ is closest to this predicted range, the range of septal $\delta^{18}\text{O}$ in any given year (~ 0.4 – 0.6‰) is not drastically muted. Septal material, however, is easier to sample using bulk sampling methods due to its higher and more consistent density, while columellar material tends to chip apart while drilling. Additionally, both septal and columellar material record a similar interannual signal and accurate annual averages (Figures 4 and 6), despite any potential differences in disequilibrium isotope fractionation, or timing of deposition. Therefore sampling septal material does not sacrifice the reconstruction of the interannual signal. Although many researchers point to the need for very high resolution sampling to accurately resolve the full amplitude of the annual cycle with skeletal geochemical tracers, a lower sample resolution is often necessary given time and budgetary constraints in generating longer coral records [*Quinn et al.*, 1996; *Crowley et al.*, 1999]. One of *Diploastrea*'s possible uses lies in generating long multicentury proxy records, approaching 800 years in length. Further, given the promise that Fiji's location holds for capturing ENSO, SPCZ, and IPO-related climate variability on interannual and interdecadal scales, we explore the use of septal material at low (roughly bimonthly) sample resolution to produce a long-term perspective of western Pacific climate. In the following discussion we focus on the Fiji *Diploastrea* $\delta^{18}\text{O}$ and Sr/Ca data generated from septal material, at continuous 1 mm sample intervals.

[22] The two Fiji *Diploastrea* colonies have mean $\delta^{18}\text{O}$ values for the 1980–1996 period that differ by only 0.13‰ which, within one standard deviation, are indistinguishable. Further, this degree of $\delta^{18}\text{O}$ disequilibrium offset is well within the 0.4‰ range that is to be expected between colonies of the same coral species growing at a given location [*Linsley et al.*, 1999]. The disequilibrium offset in $\delta^{18}\text{O}$ between *Diploastrea* and *Porites* as measured in Fiji is remarkably consistent with the offsets measured in Alor, Indonesia and New Caledonia (Table 2). While some of this intergenus offset may be due to the differences in growth rate, which as predicted yield more enriched $\delta^{18}\text{O}$ values in slower-growing coral aragonite [*McConnaughey*, 1989], *Watanabe et al.* [2003] note that intergenus differences in average $\delta^{18}\text{O}$ are surprisingly small and skeletal calcification differences cannot compensate for the vast intergenus differences in extension rate. Fiji *Porites* and *Diploastrea* differ in their skeletal extension rates only by a factor of two, while the pairs from New Caledonia and Alor, Indonesia differ by factors of 4 and 5. In spite of the much higher extension rate of Fiji *Diploastrea* compared to *Diploastrea* from Alor and New Caledonia, the comparable disequilibrium offsets between *Diploastrea* and *Porites* in all three locations suggests that the controlling factor(s) for the $\delta^{18}\text{O}$ offset is not solely a function of growth rate. Despite the complication of seawater $\delta^{18}\text{O}$, the disequilibrium offsets in $\delta^{18}\text{O}$ and Sr/Ca between *Diploastrea* and *Porites*, when converted to temperature, are strikingly consistent, both at this site and at New Caledonia and Alor, Indonesia, yielding offsets of approximately 1.6°C (Table 2). The Sr/Ca intergenus offset requires comparison to other *Diploastrea*-*Porites* pairs from different reef settings to better constrain the consistency of the offset, a necessary prerequisite before confidence in this archive can improve. However, based on *Watanabe et al.* [2003] and our results presented here, the intergenus offset seems constant over the geographic range of *Diploastrea*, which is necessary for accurate climate reconstructions.

[23] Observed differences in coral $\delta^{18}\text{O}$ between Fiji and New Caledonia, and between Fiji and Indonesia, are very consistent with the anticipated differences, and for both comparisons *Diploastrea*-based estimates are closer (within 0.04‰) than *Porites*-based estimates to calculated differences (Table 3). The results of the comparisons presented here are consistent with those of *Watanabe et al.* [2003], who found that *Diploastrea* was able to reconstruct the differences in mean climate between New Caledonia and Alor, Indonesia within 0.02‰ of the calculated value. The regional comparisons in Table 3 further suggest that regardless of the skeletal region sampled, drilling technique, or sampling density, *Diploastrea* accurately tracks regional climate differences as well as *Porites*. Such successful reconstruction of regional climate differences is a promising result in establishing the paleoclimatic utility of this coral.

[24] The Fiji *Porites* record is useful in further verifying the climate signal contained in *Diploastrea*. *Bagnato* [2003] showed that centering of the isotopic time series by subtracting the mean from these three Fiji corals reveals common interannual variance and that despite having different disequilibrium $\delta^{18}\text{O}$ offsets, all three cores are

positively correlated over the last ~30 years. Although significant correlations exist between Fiji coral $\delta^{18}\text{O}$ and climate data at a 6 point per year level [Bagnato, 2003], these correlations are forced in large part by the nature of age assignment and chronology development, while correlations for longer periods are not forced. Because of the inherent subseasonal temporal errors in the Fiji coral age models and reduced amplitude in $\delta^{18}\text{O}$ and Sr/Ca, we generated the annually averaged $\delta^{18}\text{O}$ and Sr/Ca results in Figures 8 and 9. The timing and amplitude of the interannual climate signal, based on annually averaged coral $\delta^{18}\text{O}$ (Figure 8), is very comparable in all three Fiji corals. The fact that the amplitudes of interannual and decadal-scale variability in both *Diploastrea* cores are very similar demonstrates that this archive yields a reproducible signal. In addition, the near equivalence to the *Porites* annual average $\delta^{18}\text{O}$ affirms that *Diploastrea* records average climate conditions as well as *Porites* over the last ~60 years. For *Diploastrea* Sr/Ca, the similar signal in these adjacent coral colonies is equally promising. Most coral-based paleoclimate studies have relied on geochemical analysis of a single coral colony to generate a climatic reconstruction, while relatively few composite records such as generated by Hendy *et al.* [2002] have been made. However, stacking of multiple records is typical of tree ring paleoclimate studies [D'Arrigo *et al.*, 2001; Biondi *et al.*, 2001] in order to minimize individual and local biases or noise that could obscure the regional climate signal of interest. Therefore the averaging of the two Fiji *Diploastrea* records creates a composite record that should be more reflective of regional climate (Figure 9). Comparison to indices of large-scale climate fields validates the regional climate inferences drawn from corals [Crowley *et al.*, 1999], making the SPI and NINO 4 indices very useful in evaluating *Diploastrea*'s climate reconstruction. The composite *Diploastrea* $\delta^{18}\text{O}$ and Sr/Ca records capture most major shifts in the SPI and NINO 4 Index over the last ~60 years (Figure 9), demonstrating an ability to record El Niño and La Niña conditions with more positive and negative $\delta^{18}\text{O}$ and Sr/Ca anomalies, respectively.

6. Implications and Conclusions

[25] The results of this study and that of Watanabe *et al.* [2003] have demonstrated that the coral *Diploastrea* is useful for developing climatic reconstructions. Time averaging, a significant potential problem in large-polyped

corals, may be minimized by sampling only a single skeletal region. Based on analysis of both septal and columellar material in Fiji *Diploastrea*, columellar material will yield the higher seasonal $\delta^{18}\text{O}$ amplitude than skeleton in septal areas. Complete capture of the full amplitude of the annual cycle and calculation of the most accurate $\delta^{18}\text{O}$ -, and Sr/Ca-SST relationships will require greater than 12 samples per year analysis density, given the slow and seasonally variable extension rates in *Diploastrea*. Although biased by sampling density, calibration equations for Fiji columellar and septal $\delta^{18}\text{O}$ are not significantly different, and both regions of the corallite yield comparable annual averages. Furthermore, *Diploastrea* shows sufficient consistency of vital effects across its known geographic range, regardless of sampling protocol.

[26] In the South Pacific, short and sparse site-specific instrumental data cannot begin to address long-term variability in ENSO-scale climate dynamics or establish statistically significant conclusions about decadal-scale variability. Reproducibility of coral proxy time series are essential given the lack of reliable climate data against which to test prehistorical variance. These *Diploastrea* corals have experienced the same environmental history as a neighboring *Porites* coral, a history dominated by both SST and seawater $\delta^{18}\text{O}$ variability due to the intimately linked ENSO and SPCZ. The equivalence of both Fiji *Diploastrea* records illustrates that this coral genus can yield reproducible results while intergenus equivalence on interannual timescales over the past ~60 years further verifies that *Diploastrea* can produce viable climate records as effectively as *Porites* coral colonies. If *Diploastrea*'s paleoclimatic utility can be confirmed at other locations, substantial steps can be taken toward developing a better understanding of long-term interannual and decadal climate variability in the Pacific that *Porites*-based proxy records are not long enough to capture. The growth rate and lifespan of *Diploastrea* suggest that continuous proxy records approaching 800 years could potentially be retrieved from the western Pacific and Indian Ocean in the future.

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